Peer-To-Peer Transaction Model Among Prosumers Considering Franchise Rights of Distribution Companies

Zhemin Lin, Bochun Zhan, Zihao Li, Changsen Feng, and Fushuan Wen

Abstract In developing a peer-to-peer (P2P) electricity trading mechanism for the distribution system level, it is necessary to consider the franchise rights owned by the concerned distribution company for designing an appropriate network charging model, so as to effectively compensate the distribution system investment and operating costs. Given this background, this paper proposes a prosumer P2P transaction model that takes into account the distribution company franchise and distribution network operation constraints. First, based on the leader–follower interaction relationship between the distribution company and prosumers, a two-layer game model of determining network tariffs based on electrical distance is established. Then, based on the obtained network tariffs, the Alternating Direction Method of Multipliers (ADMM) is used to determine the P2P real-time transaction power and price of the prosumers with the data privacy protected. Finally, the IEEE 33-node distribution system is employed to demonstrate the proposed method, and it is found by simulation results that interests of all prosumers can be fairly and reasonably protected, on the basis of ensuring the secure operation of the distribution network, and the distribution company can be reasonably compensated for the resulting loss of revenue due to giving up some franchise rights.

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1 Introduction

Under the premise of following market rules and ensuring the secure and stable operation of the power system, it is necessary to design a secure, transparent and fair market operation mode and transaction mechanism according to the characteristics of prosumers P2P transactions.

In order to coordinate the emerging prosumers in the electricity market, the academia circle has conducted extensive research on P2P transactions in recent years. References [1–3] proposed a multi-prosumer P2P trading market structure. References [4, 5] considered the output uncertainty of distributed renewable energy, and established a robust optimization model for P2P transactions of prosumers. The main advantage of the above P2P transaction model is that it can maximize social benefits, but centralized optimization methods cannot protect the privacy of prosumers. Reference [6] established a multi-virtual power plants electricity-carbon-backup P2P transaction model, and distributed clearing through the adaptive step size ADMM algorithm. Reference [7] established a microgrid power trading mechanism based on blockchain. The above studies realize the clearing of P2P transactions through distributed algorithms and blockchain platforms to protect the privacy of prosumers, but do not consider network operation constraints in P2P transactions. Reference [8] proposed a P2P transaction mechanism considering the operation constraints of the distribution system and the clearing method, but did not consider the network tariffs in the P2P transaction.

The existing models of determining network tariffs mainly include: pricing models based on stamp method and contract path method [9, 10], based on pricing model of network tariffs for electrical distance. Reference [11] proposed a DLMP model based on the optimal power flow model. Reference [12] established a DLMP model based on second-order cone relaxation, but its computational complexity is large and there is a certain degree of computing error. References [13–15] established a pricing model based on electrical distance, and conducted in-depth analysis on issues of grid connection tariffs between generators and loads. The above research does not consider the full recovery of the distribution company's operating costs and network loss costs, and it is difficult to achieve a reasonable distribution of benefits among multiple subjects.

In the above background, this paper will introduce the network tariffs pricing model based on electrical distance into the optimization decision-making of distribution companies. At the same time, considering the difference in time scale between the power distribution company's network tariffs price decision and the prosumer's P2P transaction decision, ADMM is used to realize the distributed clearing of P2P transactions between producers and consumers at a given network tariffs price. Finally, an example is used to verify the rationality and effectiveness of the network tariffs pricing mechanism designed in this paper.

2 Pricing Model of Network Tariffs Considering Franchise Loss

2.1 Franchise of Distribution Company

The franchise loss is caused by the fact that electricity transactions between generators and consumers do not go through distribution companies. The franchise loss function of distribution companies can be expressed as:

$$f_{\text{loss}} = R_s - R_d \tag{1}$$

$$R_s = \sum_{i \in A} \sum_{t=1}^{T} \left[\left(\varepsilon_c^t - \varepsilon_{bd}^t \right) P_{i,b}^t - C_{\text{loss}}^t \right] \tag{2}$$

$$R_d = \sum_{i \in A} \sum_{t=1}^{T} \left[P_{i,m}^t \left(\varepsilon_c^t - \varepsilon_{bd}^t \right) + \sum_{j \in A} \left| P_{ij}^t \right| \delta_{ij,\text{net}} - C_{\text{loss}}^t \right] \tag{3}$$

where A represents the set of prosumers; T represents the optimization cycle of the network tariffs price; f_{loss} represents the franchise loss of the electricity distribution company; R_s represents electricity revenue when the franchise of the electricity distribution company is not damaged; R_d represents the income of the power distribution company during the energy transaction; ε_c^t represents the electricity price of the distribution company in time period t; ε_{bd}^t is the electricity purchase price of the distribution company from the generation company in time period t; $P_{i,b}^t$ represents power purchased from the distribution company in time period t when prosumer i does not participate in P2P transactions; $P_{i,m}^t$ represents power purchased from the distribution company in time period t when prosumer i participates in P2P transactions; P_{ij}^t represents the transaction power between prosumer i and j; $\delta_{ij,\text{net}}$ represents the network connection fee price of the transaction between prosumer i and j; C_{loss}^t is the network loss cost of time period t.

2.2 Network Tariffs Pricing Model

Assume that there are two distributed prosumers i and j for P2P transactions, and the correspondingnetwork tariffs can be expressed as:

$$\delta_{ij,\text{net}} = \gamma_{\text{net}}\, C_{ij,\text{MWkm}} \tag{4}$$

where γ_{net} represents the network tariffs decided by the power distribution company to compensate for the loss of its franchise rights, and the unit is yuan $\text{MW}^{-1}\ \text{km}^{-1}$; $C_{ij,\text{MWkm}}$ represents the megawatt kilometer of P2P energy transaction for node i and node j, the unit is km.

The marginal MW-kilometer of the electricity trade between node i and node j is related to the basic MW-kilometer of node i and node j [11], which can be calculated by Eqs. (5) and (6), respectively.

$$C_{i,\text{MWkm}} = \sum_{(\alpha,\beta)\in L} f_{i,\alpha\beta}\, l_{\alpha\beta} \tag{5}$$

$$C_{j,\text{MWkm}} = \sum_{(\alpha,\beta)\in L} f_{j,\alpha\beta}\, l_{\alpha\beta} \tag{6}$$

where $C_{i,\text{MWkm}}$ and $C_{j,\text{MWkm}}$ are the basic megawatt kilometers of node i and node j, respectively, and the unit is km. $f_{i,\alpha\beta}$ and $f_{j,\alpha\beta}$ are the power flow transfer factors, which are the injection of increased unit power generation at node i and node j and the increase at any selected reference node. The power flow of the line at unit load power is calculated using the AC power flow model; $l_{\alpha\beta}$ is the reference length of the line (α, β), which is obtained by converting the line voltage level and line type into the reference line according to the cost ratio; L is the set of regional lines.

In order to make the basic MW-km of each node irrelevant to the position of the selected reference node, and to make P2P trading parties i and j each share half of the network tariffs, this paper uses the correction coefficient C_{ij} to correct the basic MW-km of each node. On the premise that the basic MW-kilometer $C_{i,\text{MWkm}}$ and $C_{j,\text{MWkm}}$ of nodes i and j is known, the correction coefficient can be calculated by Eq. (7), and then the marginal MW-km $C_{ij,\text{MWkm}}$ of P2P power trading between node i and j can be obtained, which reflects the degree to which distribution lines are used by P2P transactions between prosumers.

$$C_{ij,\text{MWkm}} = \frac{C_{i,\text{MWkm}} \pm C_{ij}}{2} = \frac{C_{j,\text{MWkm}} \mp C_{ij}}{2} \tag{7}$$

3 Two-Layer Model Framework Between Distribution Companies and Distributed Prosumers

3.1 *Distribution Company Optimization Decision Model*

The source of revenue of the power distribution company in the P2P transaction of the prosumers includes the collection of network tariffs and electricity sales fees, and the objective is to maximize the total revenue in the network tariffs price optimization cycle:

$$\max R_d = \sum_{i \in A} \sum_{t=1}^{T} \left[P_{i,c}^t \left(\varepsilon_c^t - \varepsilon_{bd}^t \right) + \sum_{j \in A} \left| P_{ij}^t \right| \delta_{ij,\text{net}} \right] - \varphi_{\text{loss}} \sum_{(\alpha,\beta) \in L} \sum_{t=1}^{T} I_{\alpha\beta}^{t\,2} r_{\alpha\beta} \tag{8}$$

$$\delta_{\text{net}}^{\min} \le \delta_{ij,\text{net}} \le \delta_{\text{net}}^{\max} \tag{9}$$

$$R_d \le R_s = \sum_{i \in A} \sum_{t=1}^{T} \left(\varepsilon_c^t - \varepsilon_{bd}^t \right) P_{i,b}^t - \varphi_{\text{loss}} \sum_{(\alpha,\beta) \in L} \sum_{t=1}^{T} I_{\alpha\beta}^{t\,2} r_{\alpha\beta} \tag{10}$$

$$\text{s.t. } (4) - (7) \tag{11}$$

where φ_{loss} is the network loss cost coefficient; $I_{\alpha\beta}^t$ is the current of the line (α, β) in time period t and r_{ab} is the resistance of the line (α, β); $\delta_{\text{net}}^{\max}$ and $\delta_{\text{net}}^{\min}$ are the upper and lower limits of the network tariffs price set by the regulatory department, respectively.

Equation (10) ensures that the distribution company's income when the franchise is damaged does not exceed the income when its franchise is not damaged, so as to protect the interests of distributed prosumers and prevent the distribution company from obtaining excess compensation.

In addition, the power distribution company should be responsible for checking the security constraints of P2P transactions to ensure that the results of P2P transactions meet the network constraints:

$$P_{\alpha\beta,F}^t = P_{\beta,z}^t + \sum_{\gamma \ne \alpha:(\beta,\gamma) \in L} P_{\beta\gamma,F}^t + r_{\alpha\beta} I_{\alpha\beta}^{t\,2} \tag{12}$$

$$Q_{\alpha\beta,F}^t = Q_{\beta,z}^t + \sum_{\gamma \ne \alpha:(\beta,\gamma) \in L} Q_{\beta\gamma,F}^t + \chi_{\alpha\beta} I_{\alpha\beta}^{t\,2} \tag{13}$$

$$V_\beta^{t2} = V_\alpha^{t2} - 2\left(r_{\alpha\beta} P_{\alpha\beta,F}^t + \chi_{\alpha\beta} Q_{\alpha\beta,F}^t \right) + \left(r_{\alpha\beta}^2 + \chi_{\alpha\beta}^2 \right) I_{\alpha\beta}^{t\,2} \tag{14}$$

$$I_{\alpha\beta}^{t2}\,V_{\alpha}^{t2} = P_{\alpha\beta,F}^{t2} + Q_{\alpha\beta,F}^{t\,2} \tag{15}$$

$$V_{\alpha,\mathrm{down}}^{2} \le V_{\alpha}^{t2} \le V_{\alpha,\mathrm{up}}^{2} \tag{16}$$

$$0 \le I_{\alpha\beta}^{t\,2} \le I_{\alpha\beta,\mathrm{up}}^{2} \tag{17}$$

where $P_{\alpha\beta,F}^{t}$ and $Q_{\alpha\beta,F}^{t}$ are the active power flow and reactive power flow of the line (α, β) during period t, respectively; $P_{j,z}^{t}$ and $Q_{j,z}^{t}$ are the active power and reactive power injected into the node β during period t, respectively; $\chi_{\alpha\beta}$ is the reactance of the line (α, β); $I_{\alpha\beta,\mathrm{up}}$ is the current upper limit of the line (α, β) in period t; V_{α}^{t} and V_{β}^{t} are the voltage modulus value of node α and node β in period t, respectively; $V_{\alpha,\mathrm{up}}$ and $V_{\alpha,\mathrm{down}}$ are the voltage upper limit and lower limit of node α, respectively.

3.2 Optimal Decision-Making Model for Prosumers Considering Network Tariffs

The objective is to minimize total energy cost of distributed prosumers:

$$\min C_{\mathrm{total}} = \sum_{i\in A}\sum_{t=1}^{T}\left(C_{i,\mathrm{dg}}^{t} + C_{i,\mathrm{bess}}^{t} + C_{i,\mathrm{re}}^{t} + C_{i,\mathrm{net}}^{t} + C_{i,\mathrm{com}}^{t}\right) \tag{18}$$

where C_{total} represents the total cost of distributed prosumers.

(1) Distributed Generator Cost:

$$C_{i,\mathrm{dg}}^{t} = C_{i,\mathrm{ope}}^{t} + C_{i,\mathrm{eqi}}^{t} = \varphi_{i,\mathrm{dg}}^{\mathrm{ope}}\,P_{i,\mathrm{dg}}^{t} + \varphi_{i,\mathrm{dg}}^{\mathrm{eqi}}\,P_{i,\mathrm{dg}}^{t} = \varphi_{i,\mathrm{dg}}\,P_{i,\mathrm{dg}}^{t} \tag{19}$$

where the distributed generator cost of prosumer i includes power generation cost $C_{i,\mathrm{ope}}^{t}$ and equipment maintenance cost $C_{i,\mathrm{eqi}}^{t}$; $P_{i,\mathrm{dg}}^{t}$ is the active power of distributed generators in time period t. $\varphi_{i,\mathrm{dg}}^{\mathrm{ope}}$, $\varphi_{i,\mathrm{dg}}^{\mathrm{eqi}}$, and $\varphi_{i,\mathrm{dg}}$ are respectively power generation cost coefficient, aging loss coefficient, and total cost coefficient.

(2) Battery Energy Storage Device Cost:

$$C_{i,\mathrm{bess}}^{t} = \varphi_{i,\mathrm{bess}}\left(P_{i,\mathrm{c}}^{t} + P_{i,\mathrm{dc}}^{t}\right) \tag{20}$$

where $P_{i,\mathrm{c}}^{t}$ and $P_{i,\mathrm{dc}}^{t}$ are respectively the charging power and discharging power of the prosumer i battery energy storage device; $\varphi_{i,\mathrm{bess}}$ is the cost coefficient of the operation.

(3) Renewable Energy Generation Costs:

$$C_{i,\mathrm{re}}^{t} = \varphi_{i,\mathrm{w}} P_{i,\mathrm{w}}^{t} + \varphi_{i,\mathrm{s}} P_{i,\mathrm{s}}^{t} \tag{21}$$

where $C_{i,\mathrm{re}}^{t}$ is the power generation cost of renewable energy unit equipment for prosumer i in period t; $P_{i,\mathrm{w}}^{t}$ and $P_{i,\mathrm{s}}^{t}$ are the output of wind turbine and photovoltaic equipment in period t; $\varphi_{i,\mathrm{w}}$ and $\varphi_{i,\mathrm{s}}$ are the kWh cost of wind power and photovoltaic equipment, respectively.

(4) Network Tariffs Cost for P2P Transactions:

$$C_{i,\mathrm{net}}^{t} = \sum_{j \in A} \left| P_{ij}^{t} \right| \delta_{ij,\mathrm{net}} \tag{22}$$

where $C_{i,\mathrm{net}}^{t}$ represents network tariffs cost of the P2P transaction of the prosumer i in the time period t.

(5) Power Purchase Fee from Power Distribution Company:

$$C_{i,\mathrm{com}}^{t} = P_{i,m}^{t} \varepsilon_{c}^{t} \tag{23}$$

where $C_{i,\mathrm{com}}^{t}$ represents the electricity purchase fee of prosumer i from distribution company.

Constraints include:

(1) Power Balance Constraints:

$$\sum_{j \in A} P_{ij}^{t} + P_{i,m}^{t} = P_{i,\mathrm{dg}}^{t} + P_{i,dc}^{t} - P_{i,c}^{t} + P_{i,w}^{t} + P_{i,s}^{t} - P_{i,L}^{t} : \quad \lambda_{i,e}^{t} \in R \tag{24}$$

$$P_{ij}^{t} = - P_{ji}^{t} : \quad \lambda_{ij}^{t} \in R \tag{25}$$

where $P_{i,L}^{t}$ represents the load of prosumer i in period t; $\lambda_{i,e}^{t}$ and λ_{ij}^{t} are the multiplier variables corresponding to the constraints.

(2) Distributed Generator Output Constraints:

$$P_{i,\mathrm{dg}}^{\min} \le P_{i,\mathrm{dg}}^{t} \le P_{i,\mathrm{dg}}^{\max} : \quad \overline{\mu}_{i,\mathrm{dg}}^{t}, \underline{\mu}_{i,\mathrm{dg}}^{t} \ge 0 \tag{26}$$

where $P_{i,\mathrm{dg}}^{\max}$ and $P_{i,\mathrm{dg}}^{\min}$ represent the upper and lower limits of distributed generator output respectively; $\overline{\mu}_{i,\mathrm{dg}}^{t}$ and $\underline{\mu}_{i,\mathrm{dg}}^{t}$ represent the multiplier variables corresponding to the constraints.

(3) Power Constraints of Battery Energy Storage Devices:

$$S_{i,\mathrm{bess}}^{t} = S_{i,\mathrm{bess}}^{t-1} + \left(\eta_{i,c} P_{i,c}^{t} - \frac{1}{\eta_{i,\mathrm{dc}}} P_{i,\mathrm{dc}}^{t} \right) \frac{\Delta t}{Q_{i,\mathrm{bess}}} : \quad \lambda_{i,\mathrm{bess}}^{t} \in R \tag{27}$$

$$S_{i,\mathrm{bess}}^{\min} \le S_{i,\mathrm{bess}}^{t} \le S_{i,\mathrm{bess}}^{\max} : \quad \overline{\mu}_{i,\mathrm{bess}}^{t}, \underline{\mu}_{i,\mathrm{bess}}^{t} \ge 0 \tag{28}$$

$$0 \leq P_{i,c}^{t} \leq P_{i,c}^{\max}: \quad \overline{\mu}_{i,c}^{t}, \underline{\mu}_{i,c}^{t} \geq 0 \tag{29}$$

$$0 \leq P_{i,\mathrm{dc}}^{t} \leq P_{i,\mathrm{dc}}^{\max}: \quad \overline{\mu}_{i,\mathrm{dc}}^{t}, \underline{\mu}_{i,\mathrm{dc}}^{t} \geq 0 \tag{30}$$

where $S_{i,\mathrm{bess}}^{t}$ is the state of charge of the battery energy storage device for time period t. $S_{i,\mathrm{bess}}^{\min}$ and $S_{i,\mathrm{bess}}^{\max}$ are the lower limit and upper limit of the state of charge of the battery energy storage device; $\eta_{i,\mathrm{dc}}$ and $\eta_{i,c}$ are the discharge and charge efficiency of the battery energy storage device, respectively; $Q_{i,\mathrm{bess}}$ is the rated capacity of the battery energy storage device; $P_{i,\mathrm{dc}}^{\max}$ and $P_{i,c}^{\max}$ are respectively the maximum discharge power and maximum charge power of the battery energy storage device; $\lambda_{i,\mathrm{bess}}^{t}$, $\overline{\mu}_{i,\mathrm{bess}}^{t}$, $\underline{\mu}_{i,\mathrm{bess}}^{t}$, $\overline{\mu}_{i,c}^{t}$, $\underline{\mu}_{i,c}^{t}$, $\overline{\mu}_{i,\mathrm{dc}}^{t}$, and $\underline{\mu}_{i,\mathrm{dc}}^{t}$ are the multiplier variables corresponding to the constraints.

(4) Renewable Energy Generating Unit Output Constraints:

$$(1-h_w)p_{i,w}^{\max} \leq p_{i,w}^{t} \leq p_{i,w}^{\max}: \quad \overline{\mu}_{i,w}^{t}, \underline{\mu}_{i,w}^{t} \geq 0 \tag{31}$$

$$(1-h_s)p_{i,s}^{\max} \leq p_{i,s}^{t} \leq p_{i,s}^{\max}: \quad \overline{\mu}_{i,s}^{t}, \underline{\mu}_{i,s}^{t} \geq 0 \tag{32}$$

where $p_{i,w}^{\max}$ and $p_{i,s}^{\max}$ are the output upper limits of wind turbines and photovoltaic equipment, respectively. h_w and h_s are the maximum curtailment rates of wind turbines and photovoltaic equipment that promote renewable energy consumption; $\overline{\mu}_{i,w}^{t}$, $\underline{\mu}_{i,w}^{t}$, $\overline{\mu}_{i,s}^{t}$, and $\underline{\mu}_{i,s}^{t}$ are multiplier variables corresponding to constraints.

(5) Transaction Power Constraints:

$$-p_{ij}^{\max} \leq p_{ij}^{t} \leq p_{ij}^{\max}: \quad \overline{\mu}_{ij}^{t}, \underline{\mu}_{ij}^{t} \geq 0 \tag{33}$$

$$0 \leq p_{i,\mathrm{m}}^{t} \leq p_{i,\mathrm{m}}^{\max}: \quad \overline{\mu}_{i,\mathrm{m}}^{t}, \underline{\mu}_{i,\mathrm{m}}^{t} \geq 0 \tag{34}$$

where $p_{ij}^{\max}$ and $p_{i,\mathrm{m}}^{\max}$ are respectively the upper limit of the P2P transaction power of the prosumer i and j and the upper limit of the power purchased by the prosumer i from the power distribution company; $\overline{\mu}_{ij}^{t}$, $\underline{\mu}_{ij}^{t}$, $\overline{\mu}_{i,m}^{t}$, and $\underline{\mu}_{i,m}^{t}$ are the multiplier variables corresponding to the constraint conditions.

3.3 Game Interaction Mechanism Between Power Distribution Companies and Distributed Prosumers

As the leader of the leader–follower game, the power distribution company determines the price coefficient of the network tariffs as the game space according to the P2P transaction needs of the distributed prosumers and the power purchase

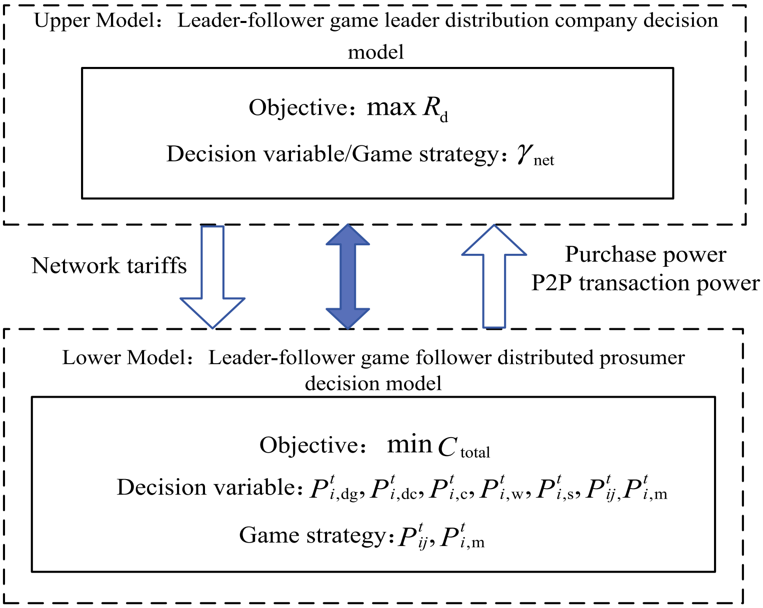

Fig. 1 Schematic diagram of leader–follower interactions in the gaming framework

demand from the power distribution company. The game strategy set of distribution company $\nu_d = \{\gamma_\mathrm{net}\}$. Distributed prosumers, as followers of the leader–follower game, have accepted the price of network tariffs. The direction of the game is to meet the load demand with the minimum total cost or to maximize the total income on the basis of meeting the load demand. The game strategy set of distributed prosumers $\nu_i = \left\{P^t_{ij}, P^t_{i,m}\right\}$ (Fig. 1).

4 Prosumer P2P Energy Transaction Distributed Clearing

Based on ADMM, the prosumer P2P transaction model including the network tariffs is solved to obtain the actual P2P transaction volume and corresponding transaction price in the transaction cycle. Global auxiliary variables $\overline{P}^t_{i,\mathrm{z}}$ can be introduced to reconstruct the original problem as:

$$\min C_\mathrm{total} = \sum_{i\in A}\sum_{t=1}^{T_\mathrm{opt}} C_i\left(\boldsymbol{P}^t_{i,\mathrm{opt}}, \boldsymbol{P}^t_{i,\mathrm{P2P}}, P^t_{i,z}, \boldsymbol{X}_i\right) \tag{35}$$

$$h_i\left(\boldsymbol{P}^t_{i,\mathrm{opt}}, \boldsymbol{P}^t_{i,\mathrm{P2P}}, P^t_{i,z}, \boldsymbol{X}_i\right) \le 0 \tag{36}$$

$$\boldsymbol{P}_{i,\mathrm{opt}}^{t} = \left[P_{i,\mathrm{dg}}^{t}, P_{i,\mathrm{dc}}^{t}, P_{i,\mathrm{c}}^{t}, P_{i,w}^{t}, P_{i,s}^{t}, P_{i,m}^{t}\right]^{T} \tag{37}$$

$$\boldsymbol{P}_{i,\mathrm{P2P}}^{t} = \left[P_{ij}^{t}, \forall j \in A\right] \tag{38}$$

$$P_{i,z}^{t} = P_{i,\mathrm{dg}}^{t} + P_{i,\mathrm{dc}}^{t} - P_{i,c}^{t} + P_{i,w}^{t} + P_{i,s}^{t} - P_{i,L}^{t} \tag{39}$$

$$g\left(\overline{P}_{i,z}^{t}, \boldsymbol{Y}\right) \leq 0 \tag{40}$$

$$\frac{P_{ij}^{t} - P_{ji}^{t}}{2} = P_{ij}^{t} \tag{41}$$

$$\overline{P}_{i,z}^{t} = P_{i,z}^{t} \tag{42}$$

where T_{opt} represents the P2P transaction optimization period; $P_{i,z}^{t}$ is the power injected into the distribution network node for the prosumer i; $\boldsymbol{P}_{i,\mathrm{opt}}^{t}$ is the decision variable set for the prosumer i equipment output and power purchase from the power distribution company; $\boldsymbol{P}_{i,\mathrm{P2P}}^{t}$ is the P2P electric energy transaction volume decision for the prosumer i variable set; $h_i\left(\boldsymbol{P}_{i,\mathrm{opt}}^{t}, \boldsymbol{P}_{i,\mathrm{P2P}}^{t}, P_{i,z}^{t}, \boldsymbol{X}_i\right)$ is the decision variable related constraints of prosumer i (24), (26)–(34), $\boldsymbol{X}_i$ is the relevant parameters of prosumer i; $g\left(\overline{P}_{i,z}^{t}, \boldsymbol{Y}\right) \leq 0$ is the network security constraints (12)–(17). Y is the distribution network related parameters. Equation (41) is rewritten from Eq. (25).

The specific solution process of the ADMM-based P2P power transaction optimization model for prosumer considering network tariffs is as follows:

Step 1: Set the initial value of iteration parameters $P_{ij}^{t,0}$, $\overline{P}_{i,z}^{t,0}$, $\lambda_{ij}^{t,0}$, $\pi_{i}^{t,0}$ and the allowable range of residual error $\varepsilon_{\mathrm{pri}}$, $\varepsilon_{\mathrm{dual}}$, $k = 1$;

Step 2: In the kth iteration, based on the optimization result of the network constraint problem of the $k-1$th iteration $\overline{P}_{i,z}^{t,k-1}$, the optimization result of the prosumer j $P_{ji}^{t,k-1}$, the sum of multiplier variables $\lambda_{ij}^{t,k-1}$ and $\pi_{i}^{t,k-1}$, the prosumer i is optimized according to Eqs. (43)–(45) to solve $\boldsymbol{P}_{i,\mathrm{opt}}^{t,k}$, $\boldsymbol{P}_{i,\mathrm{P2P}}^{t,k}$ and $P_{i,z}^{t,k}$, and send the value of the kth round of P2P selectric energy transaction to all the prosumers j who trade with it, and accept all the prosumers j who trade with it;

$$\begin{pmatrix} \boldsymbol{P}_{i,\mathrm{opt}}^{t} \\ \boldsymbol{P}_{i,\mathrm{P2P}}^{t} \\ P_{i,z}^{t} \end{pmatrix}^{k} = \underset{P_{i,\mathrm{opt}}^{t}, P_{i,\mathrm{P2P}}^{t}, P_{i,z}^{t}}{\arg\min}$$

$$= \sum_{t \in T} \left\{ \begin{array}{l} C_i\left(\boldsymbol{P}^t_{i,\mathrm{opt}}\right) + \pi_i^{t,k-1}\left(P^t_{i,z} - \overline{P}^{t,k-1}_{i,z}\right) + \frac{\rho}{2}\left(P^t_{i,z} - \overline{P}^{t,k-1}_{i,z}\right)^2 \\ + \sum_{j \in A} \left[\begin{array}{l} \left|P^t_{ij}\right|\delta_{ij,\mathrm{net}} + \lambda_{ij}^{t,k-1}\left(\frac{P_{ij}^{t,k-1} - P_{ji}^{t,k-1}}{2} - P^t_{ij}\right) \\ + \frac{\rho}{2}\left(\frac{P_{ij}^{t,k-1} - P_{ji}^{t,k-1}}{2} - P^t_{ij}\right)^2 \end{array} \right] \end{array} \right\} \tag{43}$$

$$= \sum_{t \in T} \left\{ \begin{array}{l} C_i\left(\boldsymbol{P}^t_{i,\mathrm{opt}}\right) + \frac{\rho}{2}\left(P^t_{i,z} - \overline{P}^{t,k-1}_{i,z} + \frac{\pi_i^{t,k-1}}{\rho}\right)^2 \\ + \sum_{j \in A} \left[\left|P^t_{ij}\right|\delta_{ij,\mathrm{net}} + \frac{\rho}{2}\left(\frac{P_{ij}^{t,k-1} - P_{ji}^{t,k-1}}{2} - P^t_{ij} + \frac{\lambda_{ij}^{t,k-1}}{\rho}\right)^2 \right] \end{array} \right\}$$

$$C_i\left(\boldsymbol{P}^t_{i,\mathrm{opt}}\right) = C^t_{i,\mathrm{dg}} + C^t_{i,\mathrm{bess}} + C^t_{i,\mathrm{re}} + C^t_{i,\mathrm{com}} \tag{44}$$

Step 3: Based on the optimization results of all prosumers $P^{t,k}_{i,z}$ in the kth iteration and the multiplier variables in the $k-1$ iteration, the network constraint problem is solved according to Eqs. (46) and (47), and get $\overline{P}^{t,k}_{i,z}$;

$$\overline{P}^{t,k}_{i,z} = \underset{\overline{P}^t_{i,z}}{\arg\min} \sum_{i \in A} \sum_{t \in T} \frac{\rho}{2}\left(P^{t,k}_{i,z} - \overline{P}^t_{i,z} + \frac{\pi_i^{t,k-1}}{\rho}\right)^2 \tag{45}$$

$$\text{s.t. } (12) - (17) \tag{46}$$

Step 4: Based on the results of the prosumer optimization problem and the network constraint problem of the kth iteration, the multiplier variables are updated according to Eqs. (48) and (49);

$$\pi_i^{t,k} = \pi_i^{t,k-1} + \rho\left(P^{t,k}_{i,z} - \overline{P}^{t,k}_{i,z}\right) \tag{47}$$

$$\lambda_{ij}^{t,k} = \lambda_{ij}^{t,k-1} + \rho\left(\frac{P_{ij}^{t,k} - P_{ji}^{t,k}}{2} - P_{ij}^{t,k}\right) = \lambda_{ij}^{t,k-1} - \frac{\rho\left(P_{ij}^{t,k} + P_{ji}^{t,k}\right)}{2} \tag{48}$$

Step 5: According to Eqs. (50), calculate the primary residual and dual residual of the kth iteration, and judge whether it is globally converged. If converged, go to Step 6; otherwise $k = k + 1$, and go to Step 2 again;

$$r_i^k = \sum_{i \in A} \sum_{t \in T} \left[\left(P_{i,z}^{t,k} - \overline{P}_{i,z}^{t,k} \right)^2 + \sum_{j \in A} \left(P_{ij}^{t,k} + P_{ji}^{t,k} \right)^2 \right] \leq \varepsilon_{\mathrm{pri}} \tag{49}$$

$$s_i^k = \sum_{i \in A} \sum_{t \in T} \left[\left(P_{i,z}^{t,k} - P_{i,z}^{t,k-1} \right)^2 + \sum_{j \in A} \left(P_{ij}^{t,k} - P_{ij}^{t,k-1} \right)^2 \right] \leq \varepsilon_{\mathrm{dual}} \tag{50}$$

Step 6: Output the prosumer P2P electric energy transaction plan including network tariffs, and the transaction plan should include the P2P electric energy transaction volume, transaction price, and the power purchase power from the power distribution company.

5 Case Study

5.1 Parameter Setting

The improved IEEE 33-node power distribution system is used for case study. It is assumed that there are 12 prosumers participating in P2P transactions, corresponding to prosumers a~l. The load data and output of renewable energy power generation equipment are taken from reference [11]. To simplify the analysis process, this paper sets the network tariffs price optimization cycle to be the same as the P2P transaction optimization cycle, $T_{\mathrm{opt}} = T = 24$ h. The P2P transaction interval is 1 h. The electricity price parameters are taken from Ref. [15].

5.2 Game Strategy Analysis of Power Distribution Company

Figure 2 shows the P2P transaction volume and the distribution company's revenue under different network tariffs prices. In the process of increasing the network tariffs price coefficient from zero to the equilibrium point, the profit of the distribution company gradually increases, and the P2P transaction volume of the distributed prosumers gradually decreases, which reflects the leading position of the distribution company in the game. After that, continuing to increase the network tariffs price coefficient will lead to a decline in the revenue of the power distribution company, because the excessively high network tariffs price inhibits the demand of prosumers to participate in P2P transactions. Under the optimal strategy, the power distribution company takes into account the income from the network tariffs and the revenue from electricity sales, so as to maximize the total income.

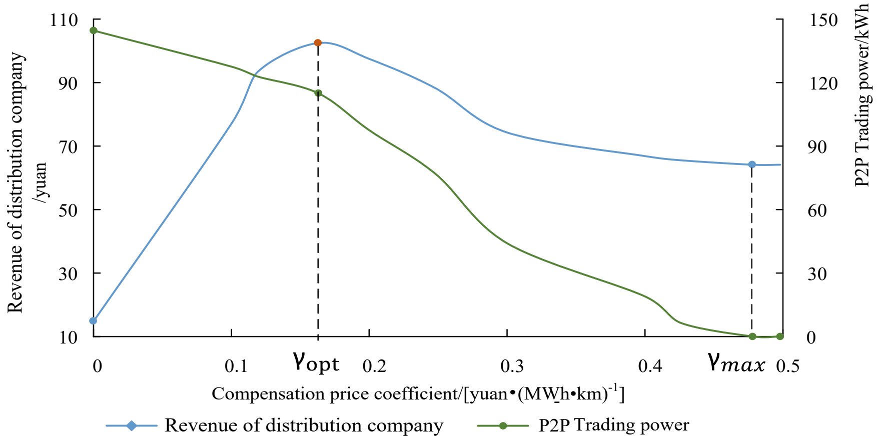

Fig. 2 Revenue of distribution company and P2P transaction amount at different prices

5.3 Distributed Prosumer P2P Transaction Analysis

Figure 3 shows the electricity consumption structure of 12 prosumers in the transaction cycle from 0:00 to 24:00, including P2P electricity transaction volume, electricity purchased from power distribution companies, and self-produced and consumed electricity. It can be seen that from 0:00 to 8:00, the proportion of P2P electric energy transaction volume in the energy consumption structure of prosumers is relatively low, and prosumers mainly meet the electric energy demand by dispatching distributed generators and energy storage devices. In 10:00–20:00, the power generation of renewable energy power generation equipment increased, and the proportion of P2P transaction volume in the energy consumption structure of prosumers increased significantly, indicating that P2P transactions promoted the consumption of distributed renewable energy.

Figure 4 shows the average price of prosumer P2P transactions in each time period. During the low electricity consumption period of 0:00–8:00, the average price of P2P transactions is close to the average network tariffs, while during the peak electricity consumption period of 11:00–14:00 and 18:00–21:00. The average price of P2P transactions is closer to the electricity sales price of power distribution companies. This is because the economic dispatchability of equipment such as distributed generators and energy storage devices of prosumers during the low power consumption period is far greater than the demand for electric energy. The power distribution company purchases very little electricity, and the power supply and demand relationship between prosumers is tense during the peak period of electricity consumption. In addition to self-scheduling, self-production, self-consumption, and P2P transactions, it is also necessary to purchase electricity from the power distribution company to meet the demand.

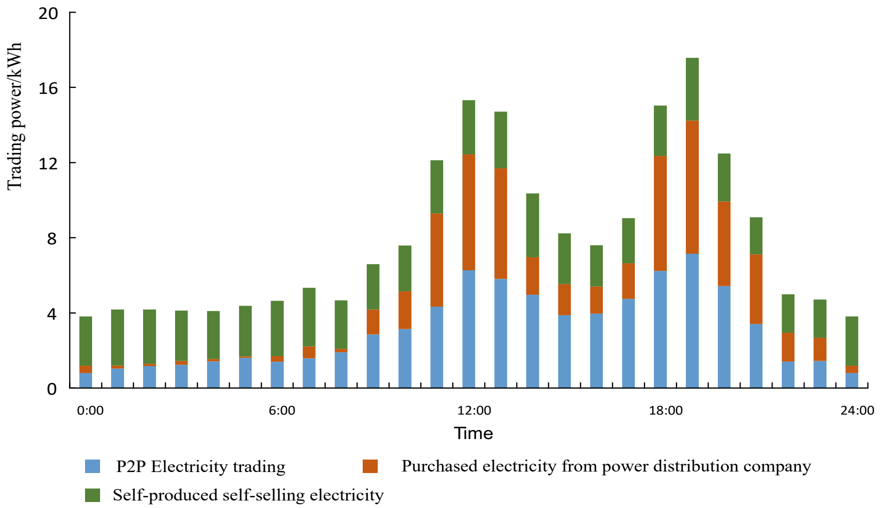

Fig. 3 Energy consumption structure of prosumers for each period

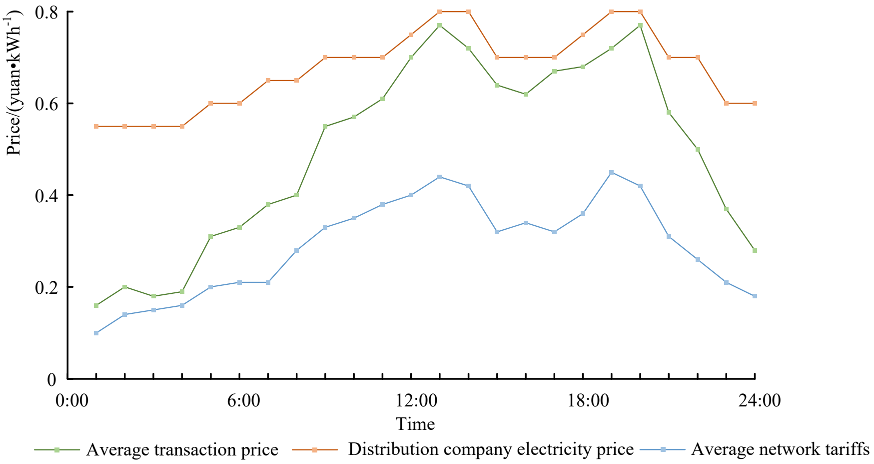

Fig. 4 Average P2P transaction price for each period

5.4 *Comparison and Analysis*

This paper compares the following three transaction models to analyze the impact of the proposed model on distributed prosumers and power distribution companies, and then illustrates the rationality and feasibility of the proposed model.

Mode 1: The P2P transaction model proposed in this paper.

Mode 2: Considering the franchise rights of power distribution companies, distributed prosumers cannot conduct electricity transactions directly, and can only use electricity themselves or purchase electricity from power distribution companies to meet demand.

Mode 3: P2P transactions can be carried out between prosumers, and the network connection tariffs can only be charged according to the cost of balancing network loss. The power distribution company provides power supply services.

Table 1 shows the results of the comparison mode. In Mode 2, after the self-optimization of 12 prosumers in the transaction cycle from 0:00 to 24:00, the total power purchase demand from the power distribution company is 203.8 kW, and the P2P transaction cost is 132.53 yuan. The total cost of electric energy is 193.05 yuan. Under this model, the total income of the power distribution company in this transaction cycle is 121.28 yuan. In Mode 3, prosumers only need to pay the network connection tariffs corresponding to the network loss cost, so the total cost is reduced, and the income of power distribution companies is greatly reduced.

In Mode 1, 12 prosumers in the trading cycle from 0:00 to 24:00 can successfully trade a total of 114.89 kW of electric energy through distributed distribution, and the total cost of distributed prosumers is 134.86 yuan, which is 30.1% less than Mode 2. In this transaction cycle, the power distribution company's network connection tariffs income is 66.31 yuan and electricity sales income is 48.76 yuan. The network loss cost is 6.33 yuan, and the total profit is 108.74 yuan, which is 1.89 times more than the total net income of Mode 3. Its franchise loss is 85.3% less.

The above results show that the power distribution company can minimize the damage to franchise rights caused by P2P transactions. At the same time, for distributed prosumers, compared with when the power distribution company is fully monopolized, it can reduce electricity costs through distributed P2P transactions. Under the optimal network tariffs price, both power distribution companies and prosumers interests are taken into account.

Table 1 Comparisons of results attained under three modes

Number	Prosumer Cost/ yuan	Distribution Company revenue/yuan			Franchise damages of power distribution companies / yuan
		Sales revenue/ yuan	Network tariffs/ yuan	Loss cost/yuan	
Mode 1	134.86	48.76	66.31	6.33	12.54
Mode 2	193.05	132.53	0	11.25	0
Mode 3	80.77	37.62	9.84	9.84	85.66

6 Conclusion

This paper establishes a prosumer peer-to-peer (P2P) transaction model that takes into account the franchise rights of distribution companies and network constraints. After analysis and comparison of numerical cases, the following conclusions are drawn.

This paper proposes a quantitative assessment method for distribution companies' franchise losses. Modeling the leader–follower game relationship between the power distribution company and the prosumer, and introducing the optimization decision of the power distribution company into the network tariffs pricing model, effectively reduces the franchise loss of the power distribution company. Based on ADMM, the distributed solution of the P2P transaction model including network tariffs can effectively protect the privacy of prosumer. Simulation analysis shows that the proposed model can achieve a win–win situation for both prosumers and power distribution companies.

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References

1. Wu Y, Yang S, Pan Z et al (2023) Complete peer-to-peer transaction mechanism for multiple prosumers without coordination entity. Autom Electr Power Syst 47(3):96–103
2. Sorin E, Bobo L, Pinson P (2018) Consensus-based approach to peer-to-peer electricity markets with product differentiation. IEEE Trans Power System 34(2):994–1004
3. Zhang F, Gao H, Wu Z et al (2022) Design of P2P trading framework for multiple prosumers in local energy market. Electr Power Autom Equipment 42(12):17–25
4. Mohan V, Bu S, Jisma M et al (2021) Realistic energy commitments in peer-to-peer transactive market with risk adjusted prosumer welfare maximization. Int J Electr Power Energy Syst 124:106377
5. Wang S, Sun G, Wu C et al (2022) Two-stage robust optimization model of multiple prosumers based on centralized-decentralized trading mechanism. Electr Power Autom Equipment 42(5):175–182
6. Shen S, Han H, Zhou Y et al (2022) Electricity-carbon-reserve peer-to-peer trading model for multiple virtual power plants based on conditional value-at-risk. Autom Electr Power Syst 46(18):147–157
7. Deng M, Tang Z, Huang Da et al (2021) Power transaction matching mechanism of microgrid based on block chain. Electr Power Autom Equipment 41(12):95–101
8. Feng C, Li Z, Shahidephour M et al (2018) Decentralized short-term voltage control in active power distribution systems. IEEE Trans Smart Grid 9(5):4566–4576
9. Ilic D (1997) Toward regional transmission provision and its pricing in New England. Utilities Policy 6(3):245–256
10. Zolezzi J, Rudnick H (2001) Review of usage-based transmission cost allocation methods under open access. IEEE Trans Power System 16(4):933–934
11. Nema S, Mashhadi H (2017) Distribution locational marginal price analysis considering technical constraints. In: 2017 Iranian conference on electrical engineering (ICEE). IEEE, Tehran, Iran, pp 1021–1025

12. Kim J, Dvorkin Y (2019) A p2p-dominant distribution system architecture. IEEE Trans Power Syst 35(4):2716–2725
13. Wen A, Huang W, Zhang H et al (2015) Analysis on transmission use of system charging methodology in UK. South Power System Technol 9(8):3–8
14. Iria J, Scott P, Attarha A (2020) Network-constrained bidding optimization strategy for aggregators of prosumers. Energy 207:118266
15. Baroche T, Moret F, Pinson P (2019) Prosumer markets: a unified formulation. Milan power technology conference. IEEE, Milan, Italy, pp 1–6